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UTILITY APPLICATION FOR UNITED STATES PATENT

FOR

**VIBRATION MOTORS**

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## VIBRATION MOTORS

### General field of the invention

The present invention relates to vibration motors.

5 Vibration motors are also known as "ultrasound" motors which refers to their preferred operating frequency, or as "piezoactive" motors which refers to their preferred excitation material.

10 The invention is particularly advantageous in application to rotary vibration motors, however it can also be applied to linear actuators, the term "vibration motor" in the present specification covering both rotary motors and linear actuators.

### 15 Summary of one possible structure for a vibration motor

A rotary vibration motor conventionally comprises at least one stator and one rotor, together with execution means for deforming said stator and/or said rotor in vibration modes that combine tangential vibrations and  
20 normal vibrations suitable for driving the rotor in continuous rotation.

Particularly advantageous vibration motor structures are proposed in particular in patent applications EP 0 907 213 and FR 98/10391 to which reference can  
25 advantageously be made. The general principle of those structures is shown diagrammatically in Figures 1 and 2.

Such a motor comprises an outer casing 2 containing two rotor disks 1 secured to a shaft 3 together with stator plates 4 between which said disks 1 are disposed.

30 Each stator plate 4 is constituted by a plurality of contact sectors 6 (referred to as stator "petals") which are angularly distributed and which are separated in pairs by active elements 7 for imparting tangential deformation (piezoelectric or other elements). The  
35 contact sectors 6 of the two inner plates 4 are in register with one another. Active elements 8 (piezoelectric or other elements) for generating a normal

force are interposed between the sectors 6 and these two inner plates 4. Spring-forming means 9 are interposed between the casing 2 and the contact sectors 6 of the outer plates 4.

5        When an active element 8 lengthens, the contact sectors 6 in register therewith clamp the rotor disks 1. When it retracts, the corresponding contact sectors 6 release the disks 1.

10        Two active elements 7 on either side of the same sector 6 are excited in phase opposition. Similarly, two adjacent active elements 8 are likewise excited in phase opposition. The active elements 8 for generating a normal force and the active elements 7 for tangential deformation are controlled synchronously so as to drive  
15        the rotors 1 in rotation.

State of the art and objects of the invention

One of the problems encountered with vibration motors is that of their efficiency.

20        Proposals have already been made to use a material having resilient properties in a reciprocating contact zone between a rotor and a stator so as to minimize energy dissipation associated with cyclic friction between the rotor and the stator.

25        In particular, French patent application FR 2 742 011 proposes using shape memory alloys which are materials having non-linear super-elasticity and which, compared with conventional materials, have the advantage of accommodating large amounts of deformation in small  
30        quantities of material.

35        The term "super-elasticity" is used throughout the present specification to designate the property whereby a material can accept reversible elongation of 1% or more. It is also recalled that the non-linear character of super-elasticity gives rise to the presence of a change-of-phase plateau in the curve of deformation as a function of traction force.

In above-mentioned patent application FR 2 742 011,  
it is shown that such a structure has the advantage of  
limiting the peaks of the applied normal force and of  
maintaining the tangential friction force at values below  
the slip threshold.

An object of the invention is to further increase  
the efficiency of vibration motors.

Application EP 0 543 114 discloses an actuator in  
which bearing contact between the fixed portion and the  
moving portion is minimized so as to ensure that energy  
losses due to friction are minimized. In the solution  
proposed in that document, the contact surface of the  
fixed part as constituted by the stator is not rigid, but  
is deformed by the propagation of a traveling wave which  
drives the moving part which constitutes the rotor. Only  
the peak of the continuous deformation then comes into  
contact with the driven part.

It will be understood that that solution does not  
make it possible to obtain high drive powers of a kind  
that would be obtainable from vibration motor structures  
as described above with reference to Figures 1 and 2 and  
operating on the principle of setting rigid sectors into  
vibration which sectors are moved bodily and not by  
continuous deformation.

#### Brief summary of the invention

The invention proposes a solution for increasing the  
efficiency of a vibration motor of the type comprising  
comprising at least one stationary part and one part  
driven to move relative to said fixed part, together with  
excitation means suitable for exerting forces that tend  
to move rigid contact sectors presented by said fixed  
part and/or said moving part and to cause said rigid  
sectors to vibrate in vibration modes that combine  
tangential vibration and normal vibration, thereby  
driving the movement of the moving part.

For the tangential vibrations or the normal vibrations, said motor presents a main resonant mode and at least one secondary resonant mode, and the proposed solution consists in that the secondary resonant mode is at a frequency which is substantially equal to a harmonic frequency of the main resonant mode.

In particular, the moving part can be a rigid disk rotor, said motor having a stator which comprises at least one pair of stator plates, each plate having rigid petals suitable for receiving means for displacing said rigid petals tangentially and normally.

In a variant, the motor can be a linear actuator.

In a first advantageous variant, at least one element having elastic deformation properties is included in the moving part and/or the stationary part, said element being separated from the contact face of said moving part and/or of said fixed part by a shoe-forming portion, and

the part(s) in which the elastic deformation elements are included is/are dimensioned in such a manner that the frequency of the secondary tangential resonant mode which is the resonant mode in which the shoe-forming portion and the remainder of the part oscillate in phase opposition, is substantially equal to a frequency which is a harmonic frequency of the main tangential resonant mode, in which the shoe-forming portion and the remainder of the part oscillate in phase.

Such a motor advantageously further includes the various following characteristics:

- the frequency of the secondary tangential resonant mode is substantially equal to twice the frequency of the main tangential resonant mode;

- it includes an array of elastic elements interposed between the shoe-forming portion and the remainder of the stationary part and/or the moving part; and

- the elastic element is made of a material presenting properties of super-elasticity.

In another, likewise advantageous variant, which can be implemented in addition to the first variant or independently thereof, the motor presents a secondary normal resonant frequency which is substantially a harmonic frequency of the main normal resonant frequency, and the excitation means comprise means for generating normal vibrations at both of these two resonant frequencies.

Such a motor advantageously further includes the various following characteristics taken singly or in any feasible combination:

- it comprises a casing containing at least two pairs of stator plates having tangential deformation active elements, and two rotor disks which extend between the plates of respective ones of said two pairs, the normal deformation active elements extending in particular between the plates of both of the two facing pairs, spring-forming means being interposed between the pairs of plates and the casing, and

it includes, between the stator plates and the spring-forming means, at least one assembly comprising a mass and an elastic deformation element, said assembly being dimensioned in such a manner that the frequency of the secondary resonant mode in which the stator plates and said mass oscillate in phase opposition, is substantially equal to an integer number of times the main resonant frequency in which the stator plates and said mass oscillate in phase, the excitation means including means for exciting normal deformation active elements at a frequency which is substantially equal to the secondary resonant frequency;

- an elastic deformation element is a normal deformation active element excited at a frequency substantially equal to the secondary resonant frequency;

- a normal deformation active element for the main resonant mode is excited by a signal which is the sum of a signal at the main resonant frequency plus a signal at the secondary resonant frequency;

5 - the secondary resonant frequency is substantially equal to an odd number of times the main resonant frequency;

- the secondary resonant frequency is substantially equal to three or five times the main resonant frequency;

10 - the frequency of the secondary resonant mode is equal to an integer number of times the main resonant frequency, with accuracy of the order of  $\frac{1}{2Q}$  where Q is the lower of the quality factors of the two resonances; and

15 - it includes at least one assembly comprising a mass and a plurality of elastic deformation elements interposed between the stator plates and the spring-forming means, the elastic deformation elements being of stiffnesses such that said elements correspond to a plurality of harmonic resonant frequencies.

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#### Description of the figures

Other characteristics and advantages of the invention appear further from the following description which is purely illustrative and non-limiting and which should be read with reference to the accompanying drawings, in which:

25 - Figures 1 and 2, described above, are diagrams respectively in cross-section and in axial section through a vibration motor constituting a possible embodiment of the invention;

30 - Figure 3 is a diagram illustrating the zone between a moving part and a stationary part of a vibration motor;

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- Figure 4 is a diagram of the oscillating system which is equivalent to the structure shown in Figure 3;

5 - Figures 5a to 5c are graphs showing variations as a function of time in the deformation of the various layers in Figure 3 (Figure 5a), of the slip speed between the layers (Figure 5b), and of the friction forces acting therebetween (Figure 5c);

- Figure 6 is a view similar to Figure 4 showing another possible embodiment of the invention;

10 - Figure 7 is a diagram showing a vibration motor structure constituting a possible embodiment of the invention;

15 - Figure 8 is a diagram showing the oscillating system equivalent to the link between the stator petals and the casing of the vibration motor shown in Figure 7, and

20 - Figure 9 is a graph showing variation as a function of time in the bearing force between a rotor and a stator, firstly when controlled in accordance with the prior art (dashed line curve) and secondly when controlled in accordance with an embodiment of the invention (continuous line curve).

#### Description of embodiments of the invention

25 The invention is described below for a rotary motor, however it naturally applies in the same manner to a linear motor.

#### Tangential vibration modes

30 Figure 3 shows an example of a possible structure for a petal 6 in a structure of the type shown in Figures 1 and 2.

35 The petal 6 is constituted by a metal block having a main portion 12, a contact shoe 11, and an array of intermediate elements 10 interposed between the portion 12 and the contact shoe 11.



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By way of example, the intermediate elements 10 are  
pegs of cylindrical or other shape, and suitable in  
particular for accepting bending deformation.

5 In a variant, they can be constituted by blades, in  
particular blades that are generally plane in shape,  
extending at rest perpendicularly to the general plane of  
the portion 12 and suitable, in particular, for deforming  
elastically in bending under the effect of a force that  
moves the contact shoe 11 relative to the portion 12  
10 parallel to the general plane relative to which they  
extend.

The elements 10 which constitute the elastic portion  
interposed between the shoe-forming portion 11 and the  
remainder of the stator (portion 12) is advantageously a  
15 semicrystalline polymer, and in particular polyether  
etherketone (PEEK).

Semicrystalline polymers, and in particular PEEK,  
have the advantage of a low modulus of elasticity, large  
elongation, excellent fatigue resistance, and good  
20 temperature behavior.

When the elastic intermediate layer is made of such  
materials, it can be constituted by a solid layer so that  
it is easier to make.

25 The main portion 12, the contact shoe 11, and the  
elements 10 can be molded as a single piece of material  
that enables the elements 10 to present elastic  
properties, e.g. a steel.

From the structure shown in Figure 3, it will be  
understood that the elements 10 do not come directly into  
30 contact with the rotor 1a or 1b, the petal 6 having a  
portion 11 constituting a contact shoe which separates  
said element 10 from the rotor 1a or 1b on which said  
petal 6 comes to bear.

Such a structure is preferable to a structure in  
35 which the pegs or blades 10 come directly into contact  
with the rotor since that would give rise to tribological  
problems and contact area would be reduced.

Nevertheless, the presence of the shoe-forming portion 11 changes the dynamic behavior of the motor because of its mass.

However, it has been found that by appropriately dimensioning the structure constituted in this way, and in particular by dimensioning the shoe-forming portion 11, it is possible to improve the efficiency of the structure.

As shown in Figure 4, such a structure can be modelled on examining the tangential oscillations generated on the shoe 11 by the vibrations generated on the active elements 7 as an oscillating system presenting:

- a first mass (portion 12 which constitutes the main portion of a petal 6);
- a first elastic element (array of elements 10);
- a second mass (shoe-forming portion 11); and
- a second elastic deformation element (active element 7) connected to a stationary node N which corresponds to the zone located in the middle of an element 7 between two successive petals 6.

Such a system having two masses and two stiffnesses presents two modes of oscillation:

- the first mode (frequency F1) is the main tangential resonant mode in which the shoe-forming portion 11 and the remainder of the petal 6 (portion 12) oscillate in phase, the frequency of this tangential main resonant mode is selected as being the excitation frequency at which the motor is operated; and

- the second mode (frequency F2) is the secondary tangential resonant mode in which the shoe-forming portion 11 and the remainder of the petal 6 (portion 12) oscillate in phase opposition, in this mode, the amplitude of the oscillation of the portion 12 of the petal is much smaller than the amplitude of the oscillation of the shoe-forming portion 11, since the mass of the portion 11 is smaller.

The inventors have found that the efficiency with which vibration is converted into continuous movement is greatly improved when the petals of the stators are dimensioned so that the frequency F2 corresponds to a harmonic of the frequency F1 ( $F2 = NF1$ , where N is an integer), and in particular when:

$$F2 = 2F1$$

In particular, it is desirable for this condition,  $F2 = 2F1$ , to be complied with to within better than 10%.

Dimensioning includes selecting the shapes and the masses of the various portions of the petals, the distribution thereof, and in particular the distribution of the elements 10, etc.

The curves given in Figures 5a to 5c show that under such circumstances, the speed of the shoe remains close to the speed of the rotor during a longer fraction of the cycle, thereby minimizing friction losses.

In Figure 5a, the curve  $Xt_{12}$  shows the tangential displacement of the portion 12 of a petal 6 while the curve  $Xt_{11}$  shows the tangential displacement of the corresponding shoe 11.

In Figure 5b, the curve shows the slip speed between the shoe 11 and the rotor it drives.

During a driving phase, the slip speed is minimized with the elements 10 and the shoe-forming portion 11 being dimensioned for increasing compliance with the condition  $F2 = 2F1$ ; sticking takes place over a large fraction of this driving phase.

During the other phase of the cycle, the slip speed becomes negative.

Figure 5c shows how the friction force between the stator and the rotor varies over time.

Naturally, the invention applies in the same manner when the oscillating elements are not included in the stator but are included in the rotor, as shown in Figure 6.

The rotor is then dimensioned so as to enable F2 -  
2F1.

Naturally, under all circumstances, the pegs or  
blades 10 are advantageously made of materials that  
present super-elasticity, and in particular linear super-  
elasticity.

Materials presenting non-linear super-elasticity  
such as shape memory alloys can also be envisaged.

It will be observed that the above description  
applies to the case of the preferred embodiment in which  
N = 2. Nevertheless, other harmonic values produce  
similar effects, but with reduced intensity. In  
addition, an odd harmonic would produce peak limiting  
effects not only in the right-hand portion of the slip  
speed (curve analogous to that shown in Figure 5b), but  
also in the left-hand portion thereof, but this is of no  
use.

#### Normal vibration modes

The vibration motor shown in Figure 7 is similar in  
structure to that shown in Figures 1 and 2 and the same  
reference numerals plus 100 are used to designate  
structural elements shown in Figure 7 that are the same  
as elements shown in Figures 1 and 2.

Thus, the structure shown in Figure 7 comprises a  
casing 102 containing two rotor plates 101 each  
interposed between two stator plates 104.

The stator plates 104 are constituted by metal  
petals 106 that are spaced apart by active tangential  
deformation elements 107.

A petal 106 is advantageously a metal petal having  
at least one elastically deformable element included  
therein. By way of example, the petal 106 includes an  
array of elements 122 such as pegs or blades in the  
vicinity of its surface, these elements 122 being  
preferably spaced apart from the contact surface of the  
petal by a shoe-forming portion thereof.

Normal deformation active elements 108 are interposed between the petals 106 of the inner two stator plates 104 (i.e. the two stator plates which are situated between the other two, which other two are referred to as "outer" stator plates).

Spring-forming means 109 are interposed between the casing 102 of the motor and the petals 106 of the two outer stator plates 104.

More precisely, each petal 106 of the outer stator plates carries a complementary mass 120 which is mounted on said petal via a normal deformation active element 121 (e.g. made of piezoelectric material), the spring-forming means 109 bearing against said mass 120.

Such a structure can be modelled as an oscillating system presenting:

- a first mass (the mass 120);
- a first elastic deformation element (the active element 121);
- a second mass referenced 123 (corresponding to two petals 16 on either side of the portion of the rotor 101 corresponding thereto); and
- a second elastic deformation element (portion of an element 108 which extends between said mass 123 and the midplane N of the elements 108, said midplane being considered as a fixed node of the system).

Such a system with two masses and two stiffnesses present two modes of oscillation:

- the first mode (frequency F1) is the main normal resonant mode in which the masses 120 and 123 oscillate in phase; the frequency of this resonant mode is selected as being the excitation frequency for the tangential and normal deformation active elements 107 and 108, the motor having excitation means for this purpose; and
- the second mode (frequency F2) is the secondary normal resonant mode in which the masses 120 and 123 oscillate in phase opposition.

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5 The mass 120 and the active element 121 are dimensioned (shape, mass, material, etc.) so that the frequency F2 is equal to  $N \times F1$  where N is an integer, and the motor has means for exciting said active element 121 at said frequency F2.

Advantageously, N is selected to be odd.

10 The thrust force then obtained is that shown in Figure 9 (continuous line curve C1) which is substantially peak limited compared with the curve obtained by exciting only the active elements 107 and 108 at the frequency F1 (dashed line curve C2).

15 It will be observed that when N is even, the peak limiting effect is also obtained, but on one side of the cycle only, only the top portion being peak limited.

In particular, it is preferable to select  $N = 3$  or  $N = 5$ , small-order harmonics providing larger effects.

Nevertheless, it is possible for N to have values other than  $N = 3$  or  $N = 5$ .

20 Because the normal mode is damped much less than the tangential mode, the relationship  $F2 = NF1$  ought preferably to be achieved with great accuracy. It is estimated that the necessary accuracy is about  $\frac{1}{2Q}$  where Q represents the lower of the quality factors of the two resonances.

25 A variant of the solution described above consists in replacing the active element or block 121 by an equivalent passive stiffness and in feeding the main actuator with excitation at a frequency  $NF1$  in addition to its fundamental excitation at the frequency F1.

30 Furthermore, in another advantageous variant, a plurality of elastic deformation elements 109 can be provided between a mass 120 and the remainder of a petal 106 said elements having different stiffnesses and consequently corresponding to different secondary resonant modes, said elements being selected so that

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